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We have proven using renormalization theory that coupled nonlinear systems exhibit universal behavior as the strength parameter and coupling parameters are varied. This qualitative as well as quantitative universality has a wide range of applicability in particular the limits of parameter ranges where free electron lasers can produce coherent waves (no chaos in electron motion) has also been studied and the results publilshed.

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FINAL SCIENTIFIC REPORT

AFOSR-87-0122

Universal Transition From Order to Chaos and Applications in Plasma Physics

Since the start of this program 6/1/88 se eral projects have been successfully completed and published. Sin lications are enclosed here a brief summary will suffice.

Chaotic Electron Motion in Free Electron Lasers

The motion of electrons in FEL's with a guide field and viggler field is nonintegrable, and therefore chaotic trajectories are possible. Since this is detrimental to the operation of the device it is important to find the parameter regimes where such a situation may arise in order to avoid these undesirable regions.

With C. Chen we have carried out a detailed analytical as well as numerical investigation of this problem, which was published in the journal Comment Plasma Phys. Controlled Fusion in 1988. We have found that when the wave fields exceeded some critical value chaotic behavior is present.

Particle Heating and Stochastic Web Diffusion

In the last few years a number of papers appeared to analyze stochastic particle diffusion, and claims have been made as to its applicability to charged particle heating. To analyze this phenomenon I investigated a realistic physical model, where the particle in a magnetic field is subject to a standing wave field. This is a realizable situation, contrary to the models investigated by others, who typically use unrealistic δ function time dependence. It was found that the stochastic web fades away with increasing particle energy, so this scheme does not lend itself to particle heating in this form. This work was published in Comments Plasma Physics and Controlled

Fusion in 1989.

Torus Structure in Higher Dimensional Hamiltonian Systems

Statistical Thermodynamics is based on the notion that mechanical systems of sufficient complexity perform quasi ergodic motion in phase space. On the other hand systems of low phase space dimensionality (3), are ergodic only in parts of phase space their spread being im[illegible] by KAM tori. In higher dimensional systems Arnold Diffusion enables particle orbits to circumnavigate many of these tori, making a larger part of phase space ergodic.

Tori surrounding stable periodic orbits (island tori) seem to be an exception. We find using analystical as well as numerical methods that within islands robust invariants exist presenting Arnold Diffusion. We developed a new method the "quasi surface of section" method (QSS) to study the structure and topology of higher dimensional tori generated by these invariants.

We give an analytical estimate of the measure of regions inaccessible to ergodic motion as the number of degrees of freedom (dimensionality of phase space) increases. It is found that the measure of these regions decreases very fast with increasing degrees of freedom, so in the limit of infinite degrees of freedom ergodicity holds overall.

This work by G. Györgyi, F. Ling and myself has been published in Phys. Rev. A in 1989.

Universal Behavior of Coupled Nonlinear Systems

This is probably the most significant accomplishment during this grant period, due to its basic nature and general applicability to a large variety of systems.

Coupled nonlinear oscillating systems are of great importance in a variety of systems (coupled p-n junctions, Josephson-junction arrays, fluid flow problems etc). We have proven (with H. Kook and F. H. Ling), that a large variety of such systems follows a universal pattern of behavior as the parameters are varied. The two parameters of importance are the strength parameter of the individual systems and the coupling strength between these systems. As these parameters are varied the system undergoes a variety of transitions: period doubling, Hopf bifurcations, pattern formation, chaotic behavior etc.

We have performed a renormalization on a system of great generality, and established that the behavior is universal in the sense that any system belonging to the universality class exhibits qualitatively as well as quantitatively the same behavior as these parameters are varied. There are two universality classes depending on the nature of coupling. If the coupling contains a linear term in addition to nonlinear terms we have one universality class, if the linear term is missing, but quadratic terms are present the second universality class arises.

For each of these classes there is a unique behavior in parameter space with well defined boundaries spearating e.g. period 2 and period 4 oscillations, Hopf bifurcation lines leading to limit cycles, chaotic behavior etc. We have investigated the cases of two coupled systems as well as the general case of many systems. This work appeared in Phys. Rev. A in (1991).

While the analysis was carried out on coupled maps, the results should also be valid for oscillations described by differential equations. We have studied numerically a variety of such systems and have demonstrated that this is in fact the case. The abstract renormalization formalism yields very practical results as demonstrated in our companion paper to appear shortly in the International Journal of Bifurcations and Chaos.

Publications

1. Rapid Convergence to the Universal Dissipation Sequence in Dynamical Systems with C. Chen and G. Györgyi, Phys. Rev. A 36, 5502 (1987).
2. Universal Strange Attractors Summer School Lectures, World Scientific, Hao Bai Lin Editor 1988.
3. Chaotic Electron Motion in Free Electron Lasers, with C. Chen, Comments Plasma Phys. Controlled Fusion, 12, 83 (1988).
4. comments on Particle Heating and Stochastic Web Diffusions, Comments Plasma Phys. Controlled Fusion 13, 77 (1989).
5. Torus Structure in Higher Dimensional Hamiltonian Systems, with G. Györgyi and F. H. Ling, Phys. Rev. A 40, 5311 (1989).
6. Universal Behavior of Coupled Nonlinear Systems, with H. Kook and F. H. Ling, Phys. Rev. 43, 2700 (1991).
7. Universal Behavior of Coupled Nonlinear Oscillators with F. H. Ling and H. Kook, International Journal of Bifurcation and Chaos, to appear.
8. Stability Chart of Coupled Dissipative Systems with F. H. Ling and H. Kook J. of Sound and Vibrations, to appear.
9. Box Counting Algorithm and Dimensional Analysis of a Pulsar J. of Computational Physics, to appear.
10. Scaling Behavior of Coupled Nonlinear Oscillators with F. H. Ling, submitted to Nonlinear Dynamics.
11. Convective Filamentation Instability of Circularly Polarized Alfven Waves, with S. P. Kuo and M. H. Whang, Phys. Fluids B, 1, 734 (1989).

Various aspects of much of this work was also presented on a variety of international meetings in invited papers in the U.S., Canada, Italy and Hungary, as well as on numerous colloquia and seminars in the U.S.